PROCEEDINGS OF SCIENCE

Using Genetic Algorithms to Evolve Antenna Gain Patterns with Greater Sensitivity to Ultra-High Energy Neutrinos

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Evolutionary algorithms utilize principles of evolution to efficiently determine solutions to defined problems. These algorithms are especially proficient at finding solutions to complex optimization problems that would likely be inaccessible through traditional techniques. The GENETIS Collaboration is developing genetic algorithms (GAs) to design antennas that are more sensitive to ultra-high energy neutrino-induced radio pulses than current detectors. Improving antenna performance is critical because UHE neutrinos are rare, with experiments requiring either massive detector volumes with stations dispersed over hundreds of km, or extraordinarily long livetimes. Optimally performing antennas are imperative to ensuring that these rare UHE neutrino events have the highest possible chance to be detected when they occur. One technique for exploring antenna response with GAs is the Antenna Response Evolutionary Algorithm (AREA), developed by GENETIS. This algorithm evolves antenna gain patterns directly with the aim of determining the optimal antenna response for a specified science goal, independent of design constraints. This research could help quantify the maximum improvement to sensitivity, which can be compared to current design capabilities and inform future improvements. This proceeding will report on advancements to the algorithm, initial results, and planned future improvements and use cases.

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1. The GENETIS Project

The GENETIS project aims to optimize complex detector designs used in astroparticle physics experiments. In a previous work [1–3], GENETIS sought to explore potential improvements to the Askaryan Radio Array (ARA) by optimizing established antenna designs. As a second application, GENETIS has written a Genetic Algorithm (GA) that evolves antenna response patterns to measure the maximum potential improvement radio neutrino experiments can achieve in the absence of geometric constraints. GENETIS is innovative in its use of artificial intelligence (AI) to optimize detector designs using strictly a science outcome as the measure of performance, alongside few others in the emerging area of machine learning and AI-informed experimental design [4]. This proceeding presents initial results demonstrating the potential for improvement in these UHE detection experiments.

Antenna design for UHE neutrino detection is challenging for a number of reasons. UHE neutrino antenna designs typically have clear geometric and deployment constraints and can be described by a large parameter space. Furthermore, given the immense scale of these experiments and the infrequency of detecting UHE neutrinos, it is essential that each detector element is designed to return the most sensitivity for its cost. These considerations, coupled with the high-dimensional parameter spaces of detector design problems, motivate the use of computer intelligence to improve upon designs made using traditional techniques. Such techniques may lead to more precise solutions that an expert would not traditionally create.

GAs were chosen from an assortment of other computational intelligence and machine learning algorithms for antenna design with GENETIS because of their effectiveness at complex optimization problems, especially when many optimal solutions could exist [5]. The use of GAs was initially motivated by the NASA ST-5 antenna, in which a simple, segmented wire antenna was designed by a GA for satellite communications [6]. GAs have also previously been used in the design of various detectors and experiments, although rarely used to optimize for a science outcome directly [7, 8].

In this investigation, GENETIS used a GA to directly evolve the antenna response instead of the antenna geometry. Doing this allows the performance of evolved individuals to be independent of geometric constraints and indicates the magnitude of potential improvement UHE detection experiments can theoretically achieve through improved antenna designs. This in turn could help guide the design of future antennas.

2. Genetic Algorithms

A GA is a heuristic search algorithm that applies the principles of natural selection to select and generate populations of solutions, referred to as individuals, which evolve toward a desired outcome. Individuals are defined by their parameters, called genes, which are a set of values representing the individual's characteristics. As the GA explores the parameter space of solutions through variation of genes, individuals are assessed by their fitness score, which describes how well an individual has performed towards its desired goal [9–11]. The ultimate goal of the GA is to maximize this fitness score. As such, a variety of selection methods are employed to choose which individuals will pass their genes on to the next generation, with individuals with higher fitness scores being more likely to be selected. However, it must remain possible for less fit individuals to be selected, as this is imperative to maintaining the diversity of the population. This in turn prevents convergence to a local maxima that represents a good but not optimal solution. After an individual is selected to influence the next generation as a parent, the GA then modifies its genes using genetic operators. These are operations used to create children that share genes with their parent(s), designed with the intent of preserving genes associated with more fit individuals while maintaining the diversity necessary to fully explore the problem's parameter space [12].

3. UHE Neutrinos

The focus of the GA discussed here is the optimization of detection of ultra-high energy (UHE) neutrinos. Detection of UHE neutrinos with energies above about 10^{18} eV [13] is an important missing piece of particle astrophysics. Such particles are immensely useful cosmic messengers, but their low flux and weakly interacting nature necessitates that experiments must operate over massive detector volumes with highly sensitive detectors.

A number of experiments employ antenna arrays to detect Askaryan radiation produced when a neutrino collides within a large volume of ice (such as in Antarctica or Greenland) [14, 15]. These experiments include ANITA, ARA, ARIANNA, and RNO-G, which utilize a variety of different antenna types [16–21]. This proceeding focuses on ARA as a use case for the optimization techniques discussed. The in-ice ARA array uses two different antenna designs to detect both vertical polarization (VPol) and horizontal polarization (HPol), which must fit in the narrow holes drilled in the ice. The ARA antennas are broadband, with the VPol antennas as birdcage bicones (13.9 cm diameter) and the HPol antennas as ferrite-loaded, quad-slot antennas (12.7 cm diameter) [22–24].

4. Antenna Response Evolutionary Algorithm

The results displayed in this proceeding were obtained using a GA developed by GENETIS, called the Antenna Response Evolutionary Algorithm (AREA), to evolve a sum of spherical harmonics used to model the radiation patterns of antennas. The spherical harmonic weights were represented by twelve variable coefficients that serve as the genes in AREA. Optimizing these genes allows for the theoretical best gain patterns to be found that maximize detector sensitivity for the ARA experiment's use case. This can then be compared with gain patterns associated with the real antennas that are currently used and their associated real world beam patterns.

The evolved coefficients define a gain pattern as calculated by Equation 1, where the coefficients $\vec{a}$ represent the weight of each spherical harmonic term and Y_l^m represent the spherical harmonics themselves. Note that only the $m = 0$ terms are included, as this analysis only considers the case of azimuthally symmetric gain patterns. The individuals in the GA are therefore given as the gain patterns defined by these thirteen azimuthally symmetric spherical harmonics given over a range of azimuth angles from 0 to 360 degrees and zenith angles from 0 to 180 degrees.

$$G(\theta, \vec{a}) \approx 2\sqrt{\pi}Y_0^0(\theta) + a_1 Y_1^0(\theta) + \ldots + a_{12} Y_{12}^0(\theta) \tag{1}$$

While there are no physical constraints considered in the creation of this gain pattern, the evolved gain patterns are however constrained to conserve energy. This is done by requiring that the gain pattern integrates over all θ and ϕ such that radiated power is equal to power received in the case of an ideal antenna.

A schematic diagram of the software for the AREA loop can be seen in Figure 1. The loop software for AREA utilizes all of the same software elements as previous GENETIS GAs [1–3], except that it no longer includes the involvement of the finite time-domain simulation software, XFdtd. Since antenna gain patterns themselves are the solutions optimized by the GA, this additional simulation step typically required to produce radiation patterns is no longer necessary.

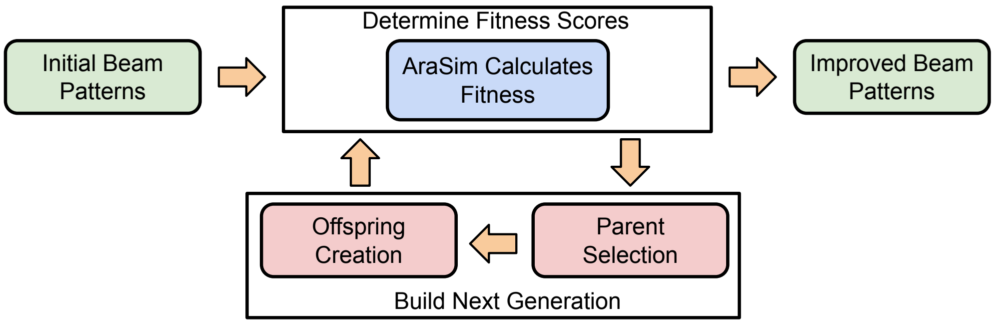


Figure 1: A diagram of the AREA software loop used to evolve antenna response patterns.

AraSim [25], the ARA Monte Carlo simulation of UHE neutrino events and detector performance, is used to inform the fitness score for the AREA GA. A given number of neutrino events are simulated, with AraSim accounting for information such as particle interactions in the ice, arrival directions, and signal propagation behaviors of the neutrino-induced signals, as well as modeling detector properties. The evolved antenna gain pattern is used in conjunction with AraSim to calculated the fitness score by setting the detector response to the evolved response. The fitness score is given by Equation 2 [26], which is the effective volume of the detector, $[V\Omega]_{\mathrm{eff}}$. The effective volume is the volume of ice to which the detector is sensitive, and is directly proportional to the number of neutrinos detected.

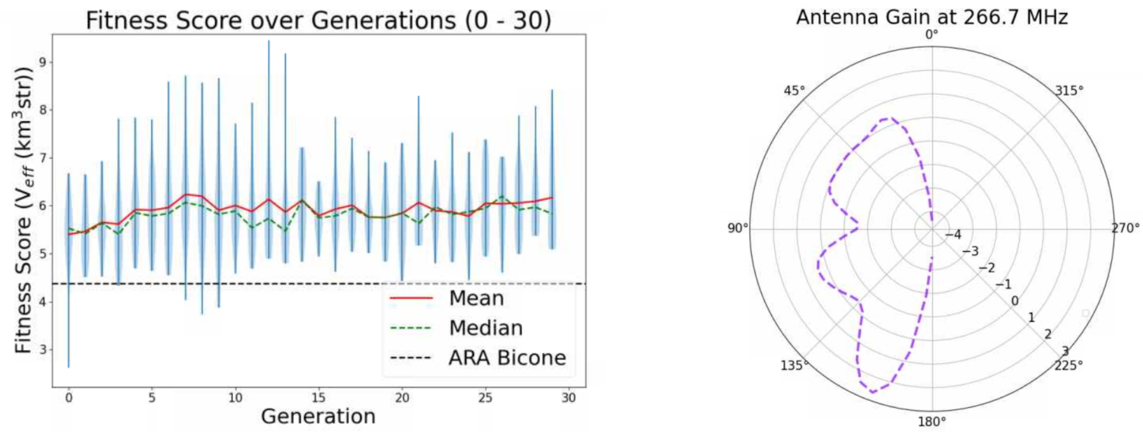
$$\text{Fitness Score} = [\mathrm{V}\Omega]_{\mathrm{eff}} = 4\pi \, \mathrm{V}_{\mathrm{ice}} \frac{\mathrm{N}_{\mathrm{detected}}}{\mathrm{N}_{\mathrm{simulated}}} \tag{2}$$

where V_{ice} is the volume of ice simulated, and N_{detected} and $N_{\mathrm{simulated}}$ are the number of neutrinos detected and simulated, respectively.

It must be noted that AraSim uses frequency-dependent gain patterns at 60 frequency steps in the band between 83.33 MHz and 1.066 GHz to determine if a simulated neutrino would be detected. As an initial study, the AREA GA currently generates a gain pattern at a single frequency that is repeated for each frequency step in the band. While AraSim is broadband, this simplified method takes the evolved antenna responses to be flat in frequency and serves as a proof of concept. Efforts to evolve frequency-dependent gain patterns to properly represent the broadband case are currently underway.

5. Results

Initial results were obtained with the AREA GA evolving single frequency gain patterns that were used at each frequency step in AraSim when calculating fitness scores. The results seen in Figure 2a depict the distributions of fitness scores formed from all individuals in each generation. A line representing the fitness score for the biconical VPol antenna design currently used by ARA is included for reference. The gain pattern found to have the highest fitness score, meaning that it was found to have the highest effective volume according to AraSim, was created in generation 12. The gain pattern of this overall highest scoring individual is shown in Figure 2b.



(a) **(b)**

Figure 2: Fitness score distributions of 20 individuals over all generations (a) and the individual with the overall highest fitness score, which was created in generation 12 (b).

These results were obtained using a population size of 20 individuals and terminating after generation 30. Parents were selected through 80% Roulette and 20% Tournament selection methods, with children generated using equal amounts of Mutation and Crossover genetic operators. Fitness scores were obtained based on 300,000 simulated neutrino events per individual in AraSim. Note that 20 individuals constitutes a fairly small population, but was chosen to decrease computation time of this initial study. Future studies will utilize an increased population size.

Additional studies were conducted to better understand the source of the improvements seen in the evolved gain patterns. Arrival directions of the simulated neutrino events detected by the evolved gain pattern were compared to those of the ARA bicone design to further quantify the difference in performance between the two designs. This was done by comparing the distribution of the cosine of the neutrino arrival angle of the simulated events detected by each design, as seen in Figure 3. Here, it is seen that the two designs detected simulated neutrinos from the same range of angles, but the evolved gain pattern detected higher event counts from most directions. Note that for this analysis, the same number of simulated neutrino events were thrown at each design, but in separate simulations.

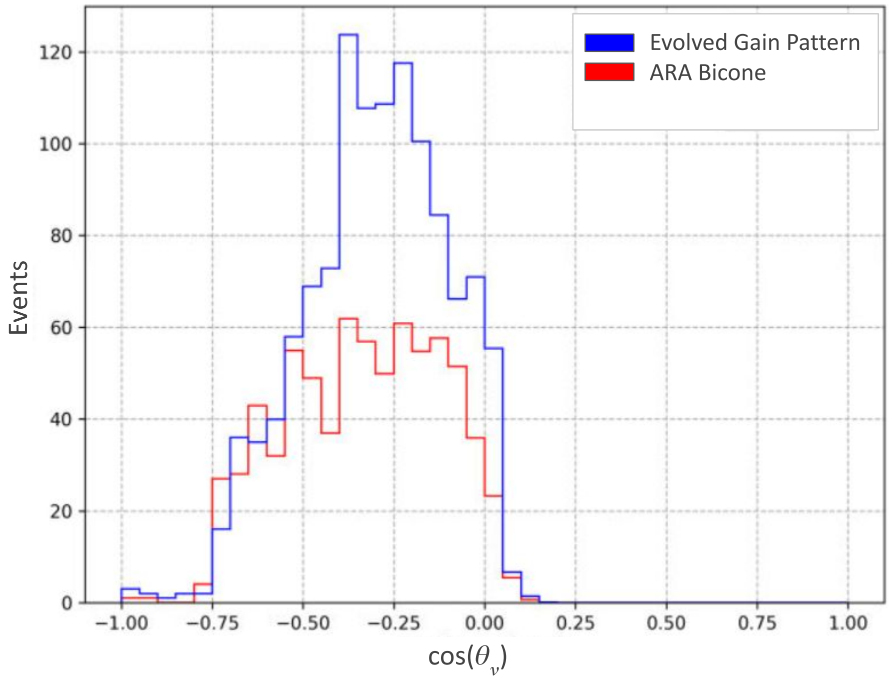


Figure 3: Histograms of detected simulated neutrino arrival directions, comparing performance of the ARA bicone design against the overall best performing gain pattern from the AREA GA.

6. Discussion

The gain pattern seen in Figure 2b is promising in that directions where the gain is the highest match physics expectations of the most common neutrino signal directions. Conversely, directions that neutrinos are rarely expected to arrive from are de-emphasized in the gain pattern. This is further underscored by the result shown in Figure 3, where it is seen that the arrival angles of detected simulated neutrinos follow a similar distribution for the gain pattern evolved with the AREA GA as that of the ARA bicone design, but with the evolved design detecting more events across nearly the full range of arrival angles.

The initial results of the AREA GA presented in this proceeding represent a promising first step, and efforts are currently underway to improve the algorithm by adding the ability to evolve frequency-dependent gain patterns that will allow it to more properly optimize broadband antenna gain patterns. Additionally, it is a priority to conduct studies to optimize the percentages of selection methods and genetic operators used during execution of the algorithm, which is expected to lead to more efficient evolution and prevent the produced solutions from reaching an early plateau, as is seen in Figure 2a. Future studies will also include larger population sizes, which will provide more opportunity for the GA to arrive at optimal solutions.

The AREA GA also has exciting potential to be interfaced with other work of GENETIS, which aims to optimize both existing antenna designs as well as those created without predefined geometry. Using an optimal gain pattern found with the AREA GA, future work could optimize antenna designs towards this gain pattern directly, potentially improving computational efficiency by better informing evolution of antenna designs.

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